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HIGH TEMPERATURE GASDYNAMICS LABORATORY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes work accomplished in three main areas during the period 15 Feb 76 to 14 Feb 78, and cites publications resulting from this work. Research is described concerning the development and testing of four-pin probes for making time and space resolved electrical conductivity measurements in MHD plasmas. In a second area, the feasibility has been demonstrated of using turnable high-resolution laser spectroscopy for measuring concentrations of infrared active species in combustion gases. The third area describes measurements of the vibrational nonequilibrium in a supersonic expansion of CO.			

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PHYSICAL PHENOMENA IN FLOWING PLASMAS AND AT
AT HIGH MAGNETIC FIELDS

1.0 INTRODUCTION

This report summarizes the research completed under AFOSR Contract F44620-76-0024 for the period 15 February 1976 to 15 February 1978. Since the results of this research have been described in detail in various publications, this report will give only brief accounts of these investigations. A summary of research results is presented in Section 2.0 and a list of publications and reports is given in Section 3.0.

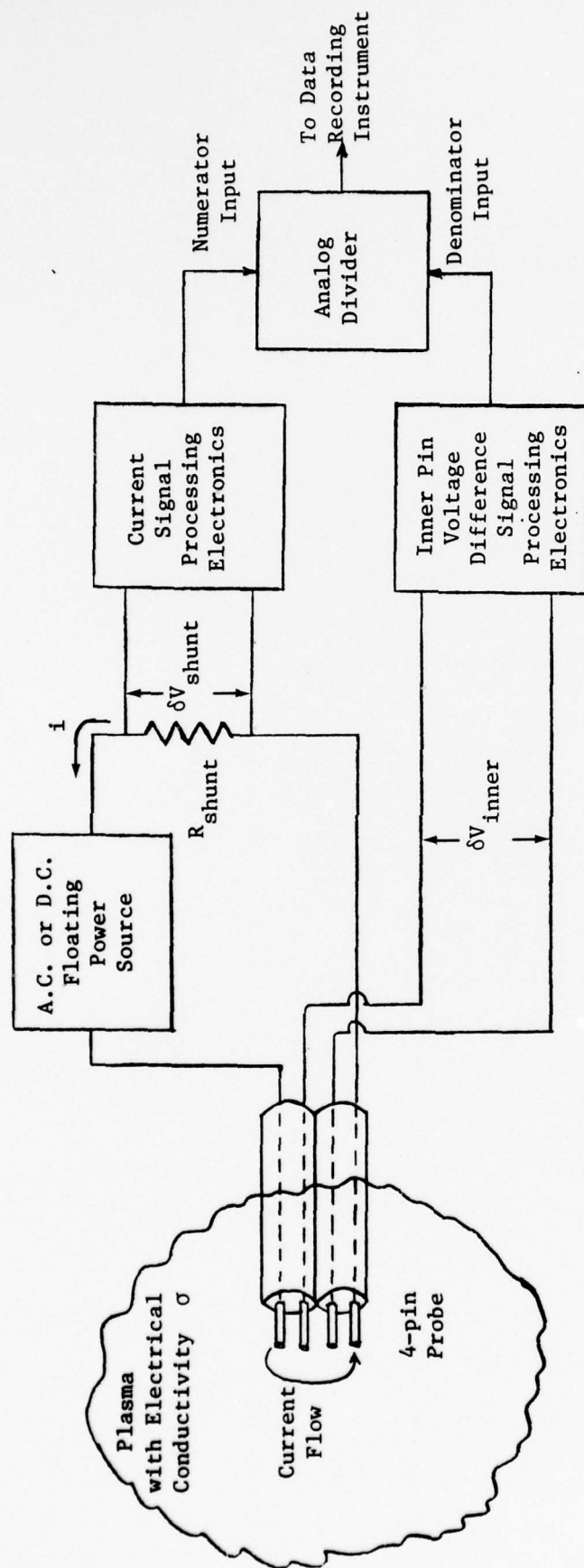
2.0 SUMMARY OF RESEARCH

Work accomplished under this contract has resulted in 2 articles that have appeared in publications that operate under some form of referee system. In addition one AFOSR Scientific Report has been published. Experimental and theoretical work has been done in three main areas; research related to MHD power generation, to combustion diagnostics, and to high power CO gas lasers. In the first area, work has been directed toward the development and testing of a four-pin probe for space and time resolved electrical conductivity measurements in MHD plasmas. In the second area, the feasibility has been demonstrated of using tunable high-resolution laser spectroscopy for measuring the concentrations of infrared active species in combustion gases. In the third area, measurements have been made of the vibrational non-equilibrium in a supersonic expansion of CO. The following sections summarize the work accomplished in each of these areas.

2.1 Measurements of Electrical Conductivity of MHD Plasmas with Four-Pin Probes

The 4-pin probe consists of four exposed tips of tungsten (or other heat resistant metal) wire in a linear array immersed in the plasmas as shown in Figure 1. If the relationship between the outer pin current i and inner pin voltage difference δV_{inner} is linear, then $\delta V_{\text{inner}} - \delta V_{\text{offset}} = (k_{\text{probe}}) (1/\sigma) (i)$, and the conductivity σ may be obtained as the slope of the $i - \delta V_{\text{inner}}$ characteristic of the probe divided by the probe constant k_{probe} . This latter quantity incorporates the geometry and detailed current distribution pattern around the pins, and is determined experimentally by measuring the probe's response when the probe is immersed in a non-flowing salt water solution whose conductivity is accurately known. Even when $i = 0$, $\delta V_{\text{inner}} = \delta V_{\text{offset}}$ is nonzero, and represents unavoidable differences in contact potential between the inner pins and the plasma. The assumptions that (a) the probe's $i - \delta V_{\text{inner}}$ characteristic is linear, and (b) the probe constant k_{probe} found empirically in non-flowing salt water remains valid when the probe is placed in a flowing plasma, are assumptions which must be experimentally verified in order to demonstrate the desired accuracy of the 4-pin probe method.

Accordingly, one major goal of the work with 4-pin probes has been to investigate to what extent the indicated reading of the probe is sensitive to "flow effects"; in particular to (a) the magnitude of the flow velocity, and (b) the angular orientation of the pins with respect to the flow direction. To vary the flow velocity, a long probe is inserted axially (by a mechanical translating mount) into a slowly converging subsonic nozzle, as indicated in Figure 2a. The mount also rotates so as to vary the orientation of the pins, as shown in Figure 2b. .



Principle of Operation: In linear region of probe characteristics,

$$\delta V_{\text{inner}} = (\text{constant}) (\text{plasma resistance}) (\text{probe current}) = \left(k_{\text{probe}} \right) \left(\frac{1}{\sigma} \right) (i),$$

$$\text{or } \sigma = k_{\text{probe}} \frac{i}{\delta V_{\text{inner}}} = \left(\frac{k_{\text{probe}}}{R_{\text{shunt}}} \right) \left(\frac{\delta V_{\text{shunt}}}{\delta V_{\text{inner}}} \right)$$

Figure 1. Schematic of Operation of 4-Pin Conductivity Probe

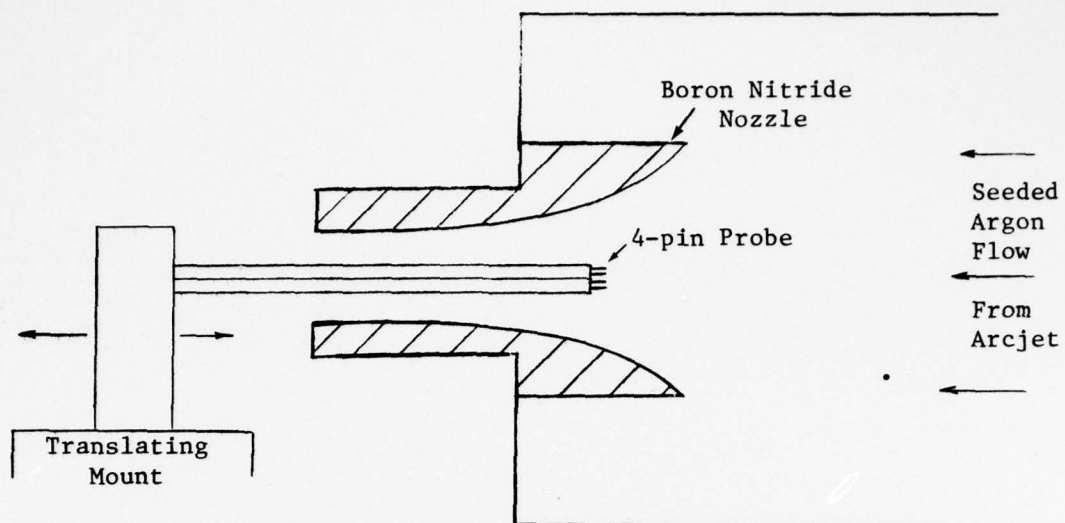


Figure 2a. Method of Varying Flow Velocity Over 4-Pin Probe.

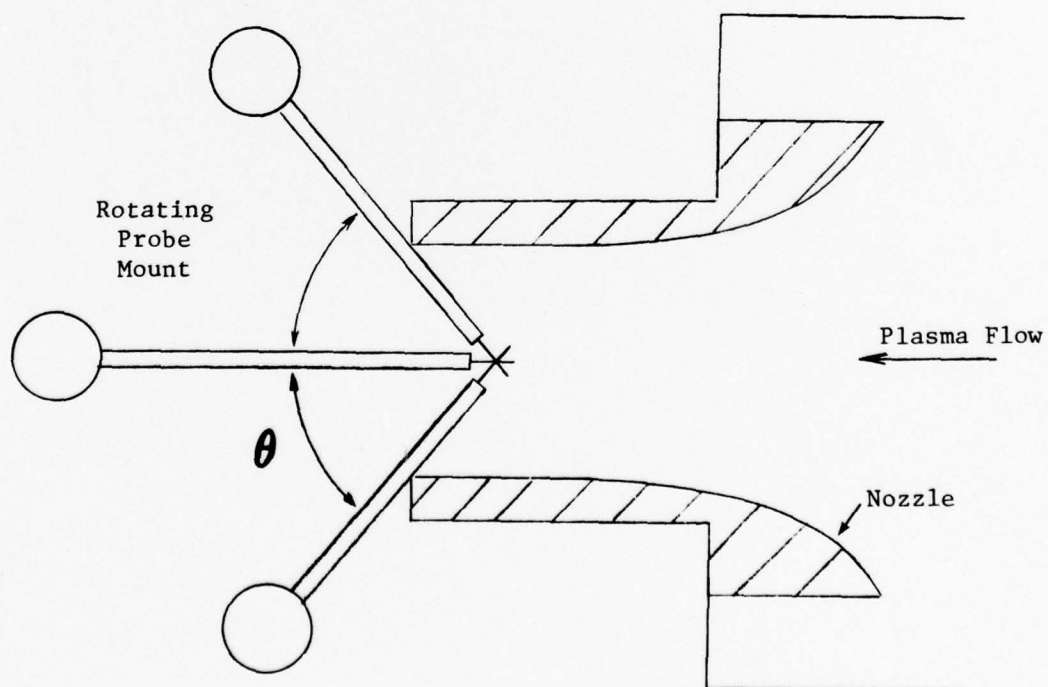


Figure 2b. Method of Varying Orientation of Pins Relative to Plasma Flow

During the course of our experimental work it became evident that the arcjet and seeding system employed was not capable of producing a plasma source as accurately steady and uniform as was desirable. Changes in the conductivity could occur irregularly and for reasons unrelated to the 4-pin probes. To deal with this problem, it was decided to operate two 4-pin probes simultaneously employing one fixed-position probe to monitor changes in the "background conductivity" and one mobile probe (as in Figure 2) to use in studying flow effects. Because of the changing background conductivity and the need to acquire data fairly quickly it became apparent that it would be desirable to have a suitable electronic signal processing system which would permit a continuous stripchart recording of a signal, coming from each probe, which is directly proportional to the indicated conductivity (i.e. proportional to the slope of the $i-\delta V_{\text{inner}}$ characteristic of the probe). The development of this electronics package for "continuous readout" of conductivity has been another major objective of the work.

The linearity of the 4-pin probe response was investigated in several experiments by slowly sweeping the outer pin applied voltage, δV_{outer} , and tracing the $i-\delta V_{\text{inner}}$ characteristics on an XY plotter. Nonlinear characteristics and even an apparent hysteresis effect were routinely observed, but it was found that good linear $i-\delta V_{\text{inner}}$ characteristics could indeed be achieved by restricting δV_{outer} to values between roughly $\pm 1/2$ volt and ± 1 volt.

The slopes of these linear $i-\delta V_{\text{inner}}$ plots yielded values of conductivity of the order of 20 mho/m, which were consistent with the seed concentration and gas temperature employed. However, even when the probe current i went to zero, there remained an appreciable non-zero inner pin voltage

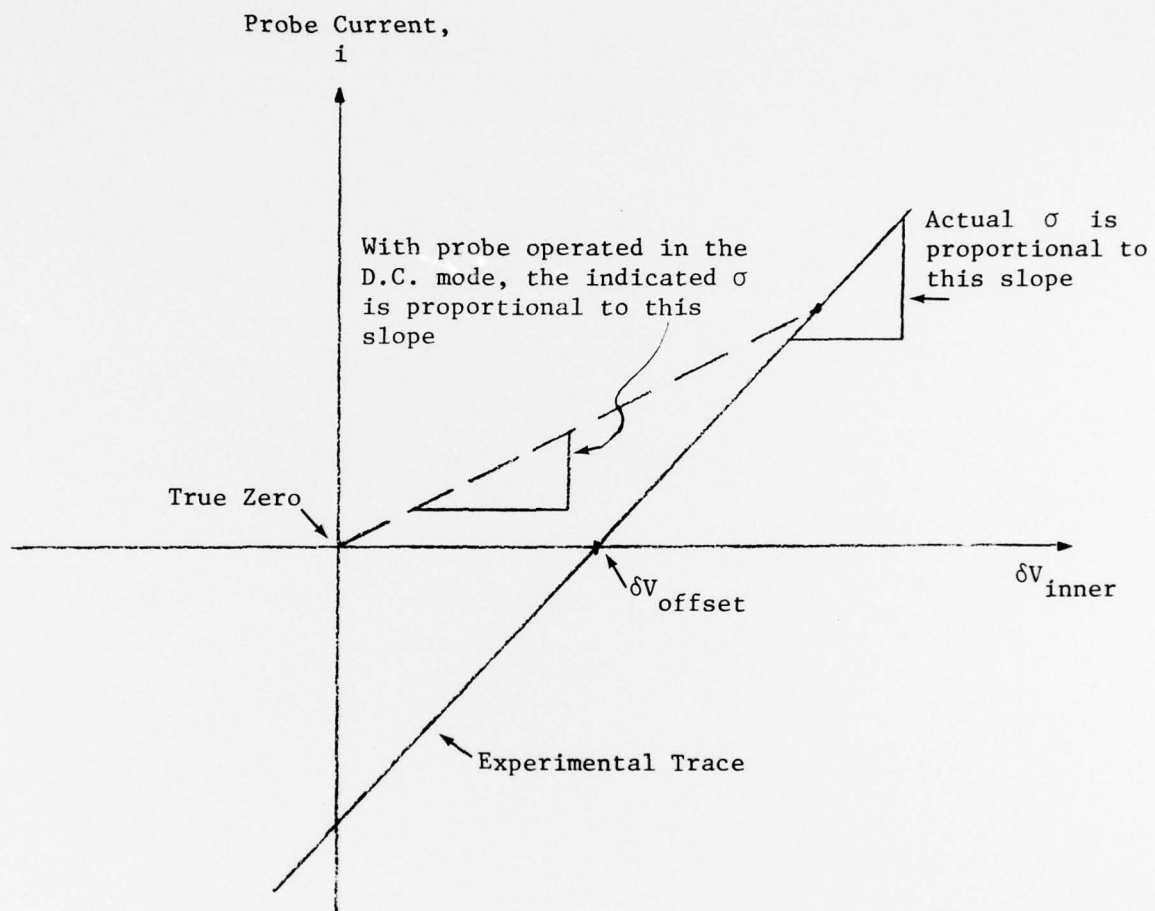


Figure 3. Typical i - δV_{inner} Plot for 4-pin Probe.

difference δV_{offset} (c.f. Figure 3). The value of δV_{offset} was not predictable, varying somewhat slowly with time and from one probe to another. The fact that δV_{offset} is finite and unpredictable means that one cannot operate the 4-pin probe in the DC mode (e.g. by applying a constant voltage between the outer pins) without incurring possibly serious errors in the indicated value of conductivity, as illustrated in Figure 3.

The final solution to the problem of δV_{offset} and the obtaining of a continuous conductivity readout was achieved with the electronics configuration whose block diagram appears in Figure 4. A brief explanation of the function of each of the components is given below, and Figure 5 shows sample waveforms obtained at each station in the signal processing chain, using a dummy probe.

The probe is excited by a floating AC power source at frequencies of the order of 20 kHz. The probe is required to be completely floating to avoid currents passing through the plasma to grounded parts of the plasma generator system. The excitation frequency of roughly 20 kHz was chosen to lie well above the highest frequencies of the naturally occurring turbulence in the flow (approximately 2 kHz, as determined experimentally) but well below RF frequencies at which capacitative and inductive impedances of the cables and circuit components would become appreciable.

The differential amplifiers maintain the isolation of the probe off ground and amplify the actual signals V_{shunt} and δV_{inner} (typically a few tens of millivolts) to the level of several volts for greater ease in subsequent processing.

The high pass filters play the important role of blocking any low-frequency noise (in particular, the undesirable δV_{offset}), and passing only

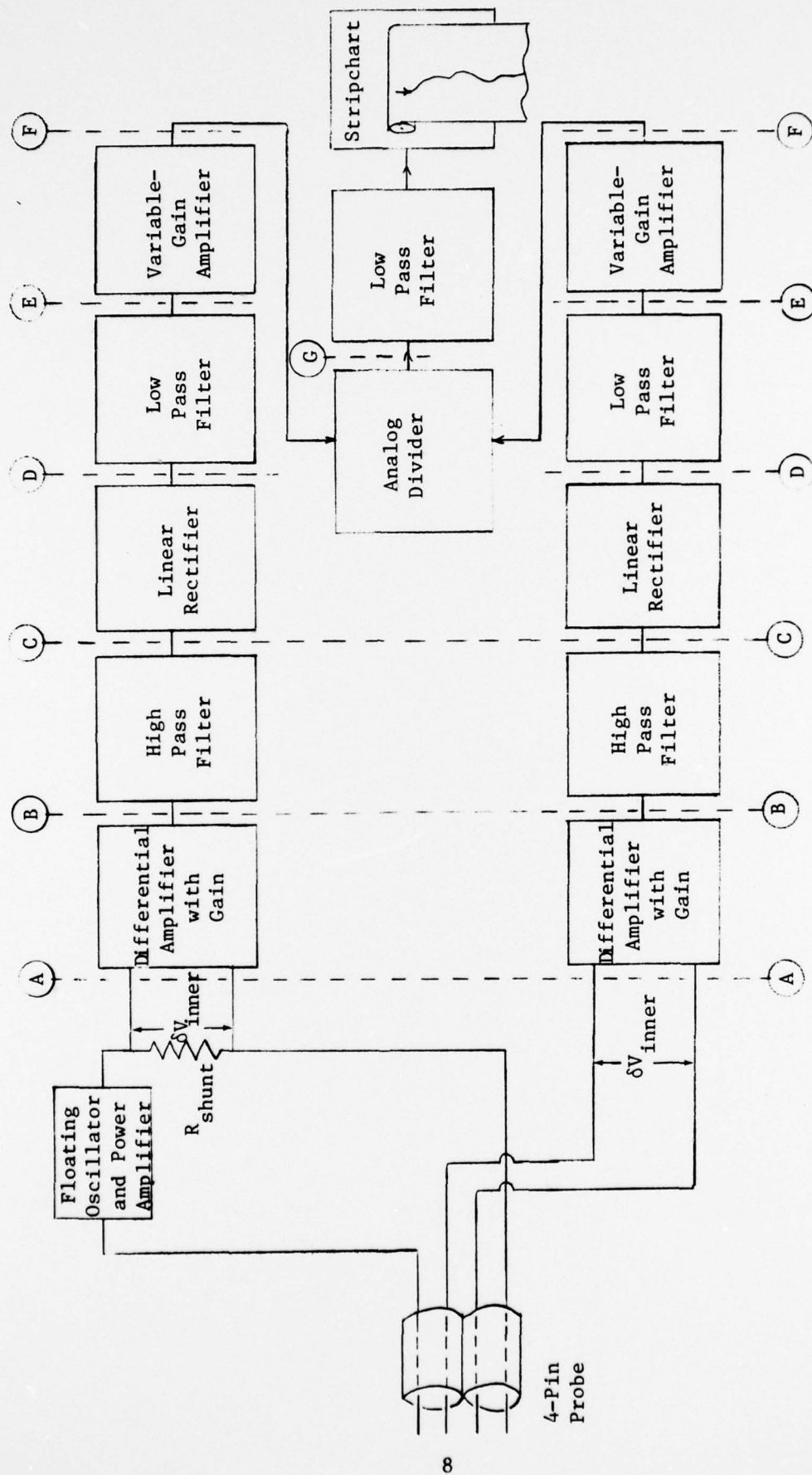


Figure 4. Block Diagram of Signal Processing Electronics Used with 4-Pin Probe.

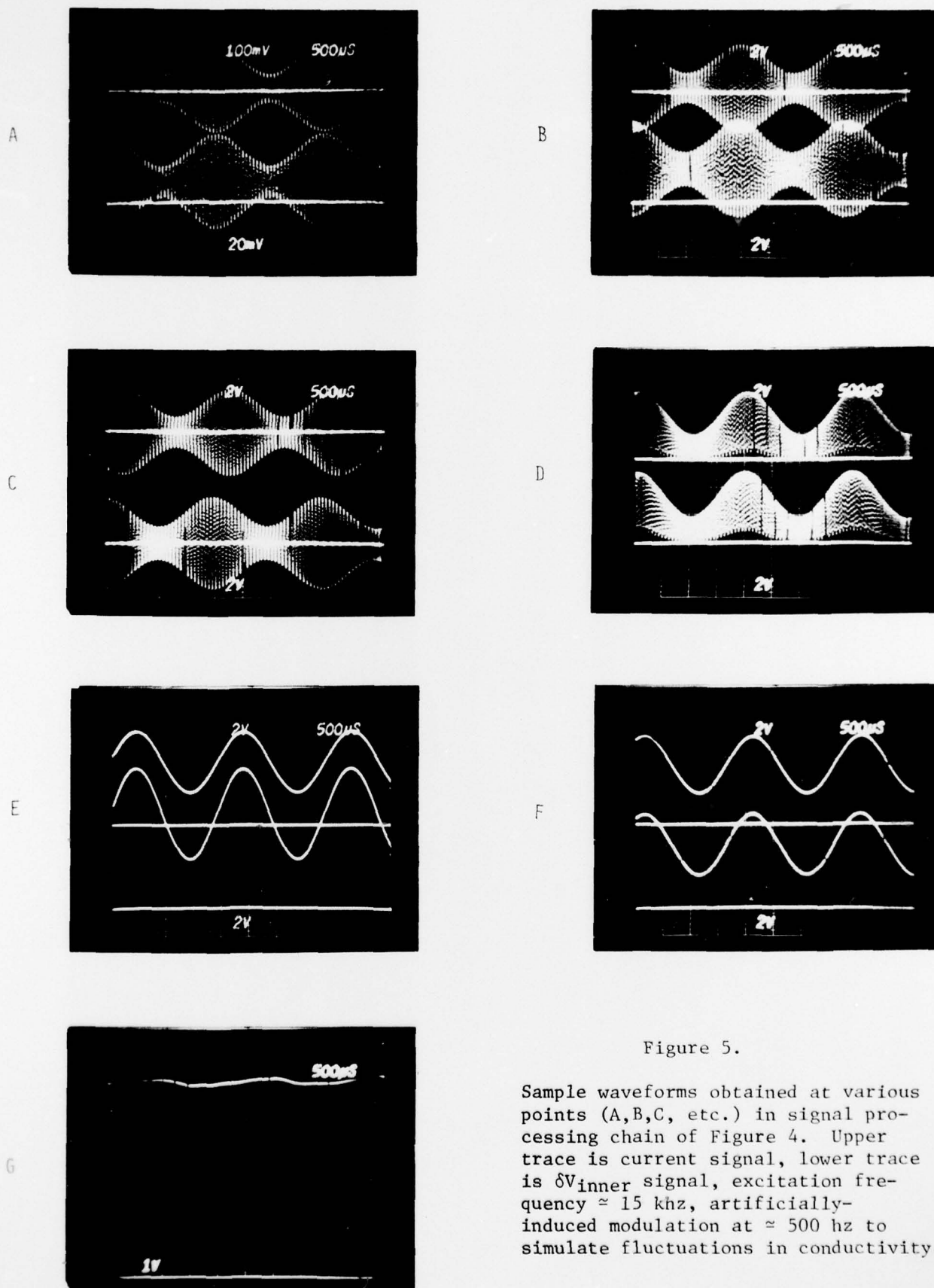


Figure 5.

Sample waveforms obtained at various points (A,B,C, etc.) in signal processing chain of Figure 4. Upper trace is current signal, lower trace is δV_{inner} signal, excitation frequency ≈ 15 kHz, artificially-induced modulation at ≈ 500 Hz to simulate fluctuations in conductivity.

those high-frequency components of the signals, which are due exclusively to the probe excitation mechanism. (Compare the lower traces on Figures 5B and 5C.) The signals emerging from these filters have the form of a "carrier" wave (at the excitation frequency, say 20 kHz) modulated in amplitude by the conductivity fluctuations, and are symmetric about ground potential. For the case where the excitation frequency is 20 kHz, the high pass filter cutoff frequency would be set typically at about 10-15 kHz.

The next two components--rectifier followed by low pass filter--perform the function of demodulating this signal and produce a positive d.c. signal whose magnitude changes in accordance with variations in the conductivity. There is one such signal arising from the probe current flowing through the shunt resistor and another from the inner pin voltage difference, each amplified by some constant gain from the electronics. If the probe is operating in the linear portion of its $i-\delta V_{\text{inner}}$ characteristic, the quotient of these two signals will be directly proportional to the slope of the characteristic, and hence to the plasma conductivity. For the case where the excitation frequency is 20 kHz, the low-pass filter would be set typically at 5-10 kHz.

Accordingly, the processed i and δV_{inner} signals are sent (after passing first through variable gain amplifiers which permit the operator to adjust the signal levels to suitable values) into the numerator and denominator inputs of an analog divider circuit, whose output signal (being the quotient of the input signals), is thus proportional to σ . The final low pass filter stage which serves to "smooth out" any conductivity fluctuations which are too rapid to be followed by the pens of the stripchart recorder. With this system, continuous monitoring of the conductivity, as indicated by both the

fixed and mobile 4-pin probes, is obtained on a single stripchart, together with signals from position transducers which monitor the axial, radial, and angular positions of the mobile probe. In addition, time-resolved measurements of σ may be made by tape recording the divider output before it is sent through the final "smoothing" low pass filter.

Once the final electronics configuration was implemented, a number of experiments were done using this system to make both time-averaged and time-resolved measurements of σ . The main conclusions which we have drawn about four-pin probes in the course of this research are as follows:

- The i - δV characteristics of the four-pin probes used remained linear if the voltage applied to the outer pins was maintained below approximately 1 volt. Depending on the particular probe geometry, the corresponding current densities at the outer pin surfaces were less than approximately 0.1 amp/cm² to 0.2 amp/cm². The criterion $V_{\text{outer}} \lesssim 1$ volt seemed to be the most practical and reliable rule of thumb for ensuring linearity.
- Even when no current passes between the outer electrodes, a finite and fluctuating voltage difference δV_{offset} appears between the inner pins; this fact requires that the probe not be operated with d.c. current if erroneous results are to be avoided.
- When excited at frequencies well above the highest naturally occurring conductivity fluctuation frequencies in the flow, the four-pin probe system described in this report appears to yield reliable and accurate time-resolved data on conductivity fluctuations (accurate in the sense that all statistical parameters characterizing the fluctuations are accurate, with the exception of the mean value of σ).

- With the method of immersion in electrolyte solutions to calibrate the probes, k_p can be found only to a precision of approximately 5% to 10% (depending on the probe used).
- For a fixed probe orientation, the indicated conductivity σ_{indic} decreases as the magnitude of the flow velocity u of the plasma increases. Experiments showed a drop of approximately 50% in σ_{indic} as u increased from about 10 m/sec to 100 m/sec.
- For a fixed flow velocity, σ_{indic} appears to decrease as the flow direction changes from "end-on" towards a sidewise orientation relative to the pin.
- The present work has not studied possible effects of the size and geometry of the probe on σ_{indic} , but has restricted attention mainly to a particular probe in the "end-on" configuration; nevertheless, it has shown that with careful, detailed measurements it is possible, for any particular probe and orientation, to produce an empirical curve of $\sigma_{indic}/\sigma_{u=0}$ vs. u which can be used as a flow-effect calibration curve, i.e., to provide a correction to σ_{indic} which would yield an accurate measure of the true local conductivity at any velocity.
- In the absence of such detailed flow-effect calibration measurements as are mentioned in the preceding conclusion, it would be unwarranted (based on the data obtained in this work) to claim high absolute accuracy for any particular four-pin probe used in flowing MHD plasmas, since the indicated conductivity may be as much as a factor of two or three lower than the actual conductivity.

2.2 High-Resolution Spectroscopy of Combustion Gases Using a Tunable Infrared Diode Laser

Tunable infrared diode lasers are well suited for in situ measurements of species concentrations and temperature in combustion gases. These lasers are also a powerful tool for determining spectroscopic parameters needed to describe the spectral characteristics of radiation from high temperature gases, such as found in engines, exhausts and plumes. The diode laser serves as a source of narrow-linewidth (10^{-5} cm^{-1}) infrared radiation whose wavelength can be rapidly modulated ($> 10^{-3} \text{ cm}^{-1}/\text{microsecond}$) to perform fast, high-resolution absorption spectroscopy. The complete fully-resolved absorption profile of a single vibration-rotation line can thus be quickly recorded, and from this one can infer the partial pressure of the absorbing species and the lineshape parameters describing the absorption line. Temperature can also be determined by measuring the relative absorption in adjacent lines originating from different vibrational levels. The ability to rapidly modulate the laser suggests that the technique can also be applied to studies of transient combustion phenomena.

Advantages of tunable diode laser absorption spectroscopy are its simplicity, high sensitivity, high spectral resolution (orders of magnitude improvement over conventional ir spectroscopy), and its fast modulation capability. The primary limitation, for some applications, is that it is a line-of-sight method. Initial work with the diode laser has demonstrated the feasibility of diode laser techniques for measuring species concentrations, temperature, and the fundamental spectroscopic parameters of line strength and collision halfwidth in laboratory combustion systems.

Experiments have been conducted in a flat flame burner and in a shock tube. In the flame experiments, the laser was used to perform high-resolution spectroscopy of CO and NO vibration-rotation transitions (near 5 microns) in the postflame region of a laminar, premixed atmospheric-pressure propane-air flame. Results with CO include fundamental data for line strengths and collision halfwidths as well as determinations of species concentrations and temperature. The measured concentrations agree well with calculated values, and the measured temperatures agree well with thermocouple measurements. In the shock tube experiments, high-resolution absorption spectroscopy of shock-heated CO was performed using the test time available behind an incident shock wave. Both sets of experiments were executed by rapidly varying the diode laser wavelength across the full width of isolated vibration-rotation lines and recording the transmitted laser intensity as a function of time (wavelength) on an oscilloscope.

A typical experimental result for a fully resolved CO absorption line in the flat flame is shown in Figure 6. The experiment was performed by modulating the laser across a single CO line ($v = 2 \leftarrow 1$, P(10) at $\nu = 2077.0 \text{ cm}^{-1}$) under fuel-rich ($\phi = 1.36$) conditions where the CO concentration was known. The measured gas temperature was 2066 K. The transmitted laser intensity for a single scan of the laser was normalized and converted to a spectral absorption coefficient using Beer's law. Figure 6 provides a comparison between the measured lineshape and a lineshape calculated assuming a Voigt profile. The data can be used to infer a line-strength [$S(T) = \int \beta d\nu$] and collision halfwidth γ under combustion conditions. The predicted absorption coefficient assuming a Voigt profile and using the inferred values

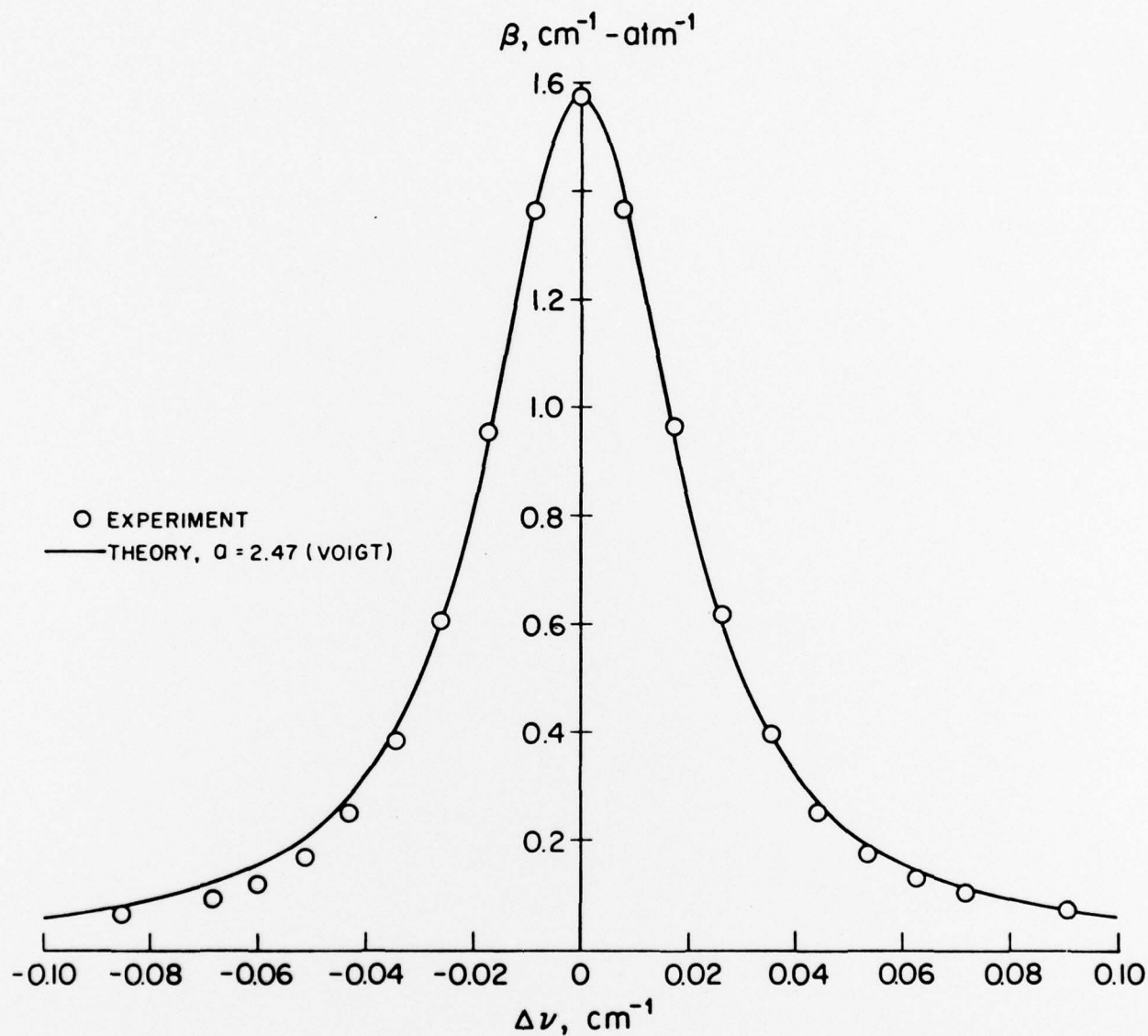


Figure 6. Comparison of calculated and measured spectral absorption coefficients for a single transition of CO ($v = 2 \leftarrow 1$, P(10)) in an atmospheric pressure, propane-air flat flame; $T = 2066$ K, $\phi = 1.36$. The best fit to the data is based on a Voigt profile with $a = 2.47$.

of S and γ agrees well with experiment. Having verified the suitability of Voigt profiles and having determined $S(T)$ and $\gamma(T)$, the same experiment can be performed to measure the CO concentration under conditions where it is not known.

2.3 Measurement of Vibrational Population Distributions in a Supersonic Expansion of Carbon Monoxide

Over the last twenty years, the phenomenon of vibrational relaxation of diatomic molecules has been an active research area. Initial measurements of the relaxation rates of vibrational energy were performed in shock heated gases (vibrational excitation flows), and it was found that these measurements could be adequately interpreted within the framework of the Landau-Teller theory [1] of vibrational relaxation of a harmonic oscillator. These data were reviewed in 1963 by Millikan and White [2], and a more recent review is available in Ref. 3.

Subsequently, measurements of vibrational relaxation rates in de-excitation flows were performed, the non-equilibrium state being created by the rapid expansion of a high enthalpy flow to supersonic conditions. It was found that if the relaxation of vibrational energy were modeled with Landau-Teller theory, a relaxation rate was inferred which was larger than that measured in an excitation flow. It has been customary to quantify the difference between the shock tube and expansion relaxation rates in terms of the ratio $\phi = (\tau_{vt})_s / (\tau_{vt})_e$, where $(\tau_{vt})_s$ is the characteristic relaxation time measured in a shock tube flow and $(\tau_{vt})_e$ is the corresponding value measured in an expansion flow. Values of ϕ have been reported in the range $5 < \phi < 10^3$ for N_2 and CO (see, for example, Refs. 4 and 5), and this series of experiments has been reviewed by Hurle [6].

The disparity in the values of vibrational relaxation rates measured in excitation and de-excitation flows stimulated a reformulation of vibrational kinetics in terms of the anharmonic model of vibrational relaxation [7]. The two models of vibrational relaxation predict significantly different characteristics for the vibrational kinetics in a de-excitation flow. The Landau-Teller theory results in an approach to equilibrium via a continuous sequence of Boltzmann distributions of the vibrational level populations [8,9] whereas the anharmonic model predicts the occurrence of non-Boltzmann population distributions, the degree of non-Boltzmann behavior being dependent on the degree of nonequilibrium and the flow history [10-14].

At the initiation of the present study, a significant body of evidence had been compiled that indicated the existence of non-Boltzmann distributions in vibrational de-excitation flows. These studies, which are reviewed in Ref. 15, included the operation of several different CO laser devices (gasdynamic, electric discharge and gasdynamic-electric discharge), and measurement of non-Boltzmann vibrational distributions in CO-N₂ microwave discharges. The modeling of these flows with the anharmonic model was successful in predicting the general qualitative features of the distribution functions observed in the corresponding experiments.

These results yielded strong support for the anharmonic description of vibrational kinetics in a supersonic expansion. However, the diagnostics used in the de-excitation experiments conducted prior to the initiation of the present study were not designed to accommodate a non-Boltzmann distribution. The interpretation of these measurements when non-Boltzmann distributions exist is discussed by Center and Caledonia [16], and the conclusion that can be drawn is that the diagnostic techniques that have been used do

not provide enough information to determine the vibrational state of the gas in the absence of a Boltzmann distribution. Consequently, the values of ϕ obtained may not be good quantitative measurements of the actual relaxation rate. The major significance of these measurements is that their apparent discrepancy with the Landau-Teller model indicated a gap in the basic understanding of vibrational de-excitation of the kinetics and has led to a more comprehensive model of vibrational energy transfer processes. Recent measurements [17] of the vibrational populations in the de-excitation flow of a CO gasdynamic-electric discharge laser have confirmed the existence of non-Boltzmann populations, in agreement with the results of the present study and predictions of the anharmonic theory.

The present study was undertaken to make an unambiguous determination of the vibrational state of carbon monoxide following a rapid supersonic expansion. The experimental technique employed was the measurement of individual vibrational populations. It was felt that these measurements, along with modeling of the flow with the anharmonic model, would yield insight into defining the important collisional mechanisms in the vibrational relaxation of a high-enthalpy expansion of a diatomic gas.

The experimental facility consisted of a supersonic nozzle and diffuser coupled to a 300 kW arc heater, providing test times of several hours duration. Arc-heated argon was seeded with CO downstream of the discharge and then expanded through the nozzle. At the nozzle exit, spectrally resolved measurements of the CO first overtone vibrational-rotational radiation were obtained with a scanning monochromator, and vibrational distribution functions were determined from these spectral records. A series of five experiments were performed with stagnation temperatures from 2000-3000 K,

and distribution functions were measured up to vibrational quantum numbers of 9 to 10. Non-Boltzmann distributions were observed in good agreement with predictions of the anharmonic model. The vibrational energy in the flow, as determined by the distribution function, did not indicate an anomalously high vibrational energy relaxation rate. The vibrational relaxation rates inferred from the present experiments agree with those measured in shock tube flows within the uncertainty of the measurements.

3.0 PUBLICATIONS AND REPORTS

1. "Measurements of Electrical Conductivity of MHD Plasmas with Four-Pin Probes," N. L. Hower, AFOSR Scientific Report TR 78-0847.
2. "High-Resolution Spectroscopy of Combustion Gases Using a Tunable ir diode laser," R. K. Hanson, P. A. Kuntz, and C. H. Kruger, Appl. Optics 16, p. 2045 (August, 1977).
3. "Measurement of the Vibrational Populations Distributions in a Supersonic Expansion of Carbon Monoxide," D. J. Bender, M. Mitchner, and C. H. Kruger. Paper accepted for publication in Physics of Fluids. (See also Stanford University Institute for Plasma Research Report No. 622, March 1975.)

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